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## **Hadronic B decays at BABAR**

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# HADRONIC $B$ DECAYS AT $BABAR$

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By means of hadronic  $B$  decays, the  $BABAR$  experiment aims to constrain the CKM matrix performing  $CP$  parameter measurements. It also seeks to test QCD factorization predictions and other models for  $B$  structure and decay mechanisms. We will present some of the on-going  $CP$  related analyses in the first section, while the second section will be dedicated to report on the conducted investigations on subjects as diverse as probing the gluon component in the  $B$  meson wave function, new physics and final state interactions in annihilation processes, intrinsic charm searches and first observation of strange charmed baryon production in  $B$  decays.

## 1. $CP$ related analyses

In this section we report on on-going hadronic  $B$  decays measurements of branching fractions and  $CP$  asymmetries which are defined, for the  $B \rightarrow f$  decay, as :

$$\mathcal{A}_{CP} = \frac{\mathcal{B}(B \rightarrow f) - \mathcal{B}(\bar{B} \rightarrow \bar{f})}{\mathcal{B}(B \rightarrow f) + \mathcal{B}(\bar{B} \rightarrow \bar{f})}$$

These are the first steps in analyses that could be used, in the future, to measure CKM matrix parameters like  $\gamma \equiv \arg \left[ -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right]$  or a combination of  $\gamma$  and  $\beta \equiv \arg \left[ -\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*} \right]$ .

### 1.1. Measurement of the branching fraction and decay rate asymmetry of

$$B^- \rightarrow D_{\pi^+\pi^-\pi^0} K^-$$

The decays  $B \rightarrow D^{(*)0} K^{(*)}$  can be used to measure the angle  $\gamma$  taking advantage of the interference between  $b \rightarrow u\bar{c}s$  and  $b \rightarrow c\bar{u}s$  decay amplitudes. Different approaches have been developed, among which  $\gamma$  measurements involving  $D$  decays to multi-body, using a Dalitz plot analysis technique as described in reference [1]. In this analysis, we measure the branching fraction of the decay modes  $B^- \rightarrow D^0(\bar{D}^0)K^-$  with the  $D^0$  ( $\bar{D}^0$ )-decay :  $D^0(\bar{D}^0) \rightarrow \pi^+\pi^-\pi^0$ , which is Cabibbo suppressed. They yield a much smaller event sample compared to Cabibbo allowed  $D$  decays but the interfering  $D^0$  and  $\bar{D}^0$  amplitudes have similar magnitudes. Therefore, the sensitivity to  $\gamma$  of this  $D$  decay channel is expected to be

relevant. In addition, due to interference, the production rate may differ from the product  $\mathcal{B}_{prod} \equiv \mathcal{B}(B^- \rightarrow D^0 K^-) \times \mathcal{B}(D^0 \rightarrow \pi^+\pi^-\pi^0) = (4.1 \pm 1.6) \times 10^{-6}$  by up to about  $0.2\mathcal{B}_{prod}$  [2]. From a sample of 229 million of  $B\bar{B}$  pairs, we found  $133 \pm 23$  signal events which correspond to a branching ratio of  $\mathcal{B}(B^- \rightarrow D_{\pi^+\pi^-\pi^0} K^-) = (5.5 \pm 1.0 \pm 0.7) \times 10^{-6}$ . We determine the raw asymmetry and do not find any significant deviation from zero :  $\mathcal{A}_{CP}^{raw} = 0.02 \pm 0.16 \pm 0.03$ . The  $\gamma$  extraction is underway using the full Dalitz analysis of the  $D$ -decay [3].

### 1.2. Measurement of the branching fraction $B^0 \rightarrow \bar{D}^0(D^0)K^+\pi^-$

To determine the feasibility of measuring  $\gamma$  with the method proposed by R. Aleksan et al. [4], that uses three-body  $B \rightarrow DK\pi$  decays, we have studied  $\bar{D}^0(D^0)K^+\pi^-$  final states with  $205fb^{-1}$  data sample. In these modes, the CKM suppressed  $b \rightarrow u\bar{c}s$  processes contain color allowed diagrams, resulting in larger rates and more significant  $CP$  violation effects than the two-body  $B \rightarrow DK$  decays. We measured  $\mathcal{B}(B^0 \rightarrow \bar{D}^0 K^+\pi^-) = (8.6 \pm 1.5 \pm 1.0) \times 10^{-5}$  combining  $D$  modes ( $D^0 \rightarrow K\pi$ ,  $D^0 \rightarrow K\pi\pi^0$ ,  $D^0 \rightarrow K\pi\pi\pi$ ) and excluding  $B^0 \rightarrow D^{*-}(2010)K^+$  contribution. Using Dalitz analysis we identified two resonant contributions:  $\mathcal{B}(B^0 \rightarrow \bar{D}^0 K^{*0}) \times \mathcal{B}(K^{*0} \rightarrow K^+\pi^-) = (3.9 \pm 0.6 \pm 0.4) \times 10^{-5}$  and  $\mathcal{B}(B^0 \rightarrow D_2^{*-}(2460)K^+) \times \mathcal{B}(D_2^{*-}(2460) \rightarrow \bar{D}^0\pi^-) = (1.9 \pm 0.4 \pm 0.3) \times 10^{-5}$ . We also set an

upper limit at 90% CL on the CKM suppressed channel:  $\mathcal{B}(B^0 \rightarrow D^0 K^+ \pi^-) < 1.9 \times 10^{-5}$ . However, we come to the conclusion that measuring  $\gamma$  is very difficult with this mode and that approximately  $2000 fb^{-1}$  are necessary to constrain  $\gamma$  within  $\pm 50^\circ$  at  $3\sigma$  level.

### 1.3. Search for $B \rightarrow D_s^+ X_{light}$ with $X_{light} \equiv \pi^0, a_0^-, a_1^-$

The value of  $\sin(2\beta + \gamma)$  can be extracted from the measurement of the time dependent  $CP$  asymmetry in  $B^0 \rightarrow D^- X_{light}^+$  decays where  $X_{light}^+ \equiv \pi^+, a_0^+, a_2^+$ . In this case, the asymmetry is given by:  $\mathcal{A}_{CP}(\Delta t) = r \times \sin(2\beta + \gamma) \times \sin(\Delta m_d \Delta t)$  where  $r = \mathcal{B}(B^0 \rightarrow D^+ X_{light}^-) / \mathcal{B}(B^0 \rightarrow D^- X_{light}^+)$ . The decay  $B^0 \rightarrow D^+ X_{light}^-$  is doubly Cabibbo suppressed and difficult to measure directly. Using  $SU(3)$  flavor symmetry, it is possible to infer the value of  $\mathcal{B}(B^0 \rightarrow D^+ X_{light}^-)$  from the value of  $\mathcal{B}(B \rightarrow D_s^+ X_{light})$ , the latter being less suppressed.

If  $X_{light}^+ \equiv \pi^+$ , then  $r$  is expected to be very small ( $r \approx 0.02$ ) which implies a small asymmetry. In this case  $r$  may be deduced from the rate  $\mathcal{B}(B^+ \rightarrow D_s^+ \pi^0)$ . We measure this branching ratio from a sample of 124 millions of  $B\bar{B}$  pairs, we do not see any significant signal and quote an upper limit at 90% CL of:  $\mathcal{B}(B^+ \rightarrow D_s^+ \pi^0) < 2.8 \times 10^{-5}$  in agreement with a previous measurement by CLEO ( $< 2.4 \times 10^{-4}$  from ref. [2]) and with the value of  $0.9 \times 10^{-5}$  expected from the rate of  $\mathcal{B}(B^0 \rightarrow D_s^+ \pi^-)$  measured by Belle and BABAR experiments. If  $X_{light}^+ \equiv a_0^+(a_2^+)$ ,  $r$  might be quite large. This is due to the coupling constant of the  $W$  to the  $a_0$  scalar meson ( $a_2$  tensor meson) which is small and decreases the production rate of the Cabibbo allowed decay  $B^0 \rightarrow D^- a_0^+(a_2^+)$ . The factorization hypothesis predicts a similar rate for Cabibbo allowed and Cabibbo suppressed decays [5] which results in  $r \approx 1$ . These decays are not yet within the experiment reach (branching ratios around  $10^{-6}$ ), nevertheless, the theoretical predictions can be tested with the measurement of the branching ratio of the decay  $B^0 \rightarrow D_s^+ a_0^-(a_2^-)$  expected at larger values:  $\mathcal{B}(B^0 \rightarrow D_s^+ a_0^-(a_2^-)) \approx 7.5(1.5) \times 10^{-5}$  (ref. [5,6]).

From a sample of 230 million of  $B\bar{B}$  pairs, we measure these two branching ratios. The  $a_0^-$  ( $a_2^-$ ) is reconstructed in  $a_{0(2)}^- \rightarrow \eta(\rightarrow \gamma\gamma)\pi^+$  which has a branching ratio of the order of 100 % (only 15 % for the  $a_2^-$ ). We do not find any significant signal and quote the upper limits at 90% CL:  $\mathcal{B}(B^0 \rightarrow D_s^+ a_{0(2)}^-) < 4.0(25) \times 10^{-5}$  which shows a discrepancy of at least a factor two with the theoretical prediction for  $a_0$ .

### 1.4. Charmless decays

The decay  $B^+ \rightarrow K^{*+}(\rightarrow K^+ \pi^0)\pi^0$  and its  $CP$  asymmetry are particularly interesting in light of the recent measurement of direct  $CP$  violation in the decay  $B^0 \rightarrow K^+ \pi^-$  [7]. It may provide valuable test of theoretical models such as those based on QCD factorization or  $SU(3)$  flavor symmetry. It has been argued that the influence of final state interactions like charming penguins and similar long distance rescattering effects on both the branching fraction and  $CP$  asymmetry of  $B \rightarrow K\pi$  decays may be significant. From a sample of 232 million of  $B\bar{B}$  pairs we find  $88.5 \pm 25.7$  signal events which correspond to the branching ratio:  $\mathcal{B}(B^+ \rightarrow K^{*+} \pi^0) = (6.9 \pm 2.0 \pm 1.3) \times 10^{-6}$  and we do not find any hint of direct  $CP$  violation:  $\mathcal{A}_{CP} = 0.04 \pm 0.29 \pm 0.05$  [8]. These results do not rule out the charming penguins hypothesis considering the large values of the uncertainties for both the branching ratio and the  $CP$  asymmetry.

## 2. Selection of other recent analyses

### 2.1. Measurement of the $B^0 \rightarrow D^{*-} D_s^{*+}$ and $D_s^+ \rightarrow \phi \pi^+$ branching ratios

We present two measurements of the branching ratio  $\mathcal{B}(B^0 \rightarrow D^{*-} D_s^{*+})$  which lead to a precise determination of the reference  $\mathcal{B}(D_s^+ \rightarrow \phi \pi^+)$ . They have been performed on a sample of 123 million of  $B\bar{B}$  pairs. The  $B^0 \rightarrow D^{*-} D_s^{*+} \rightarrow (\bar{D}^0 \pi^-)(D_s^+ \gamma)$  decay is reconstructed using two different methods. The first one combines the fully reconstructed  $D^{*-}$  with the photon from the  $D_s^{*+} \rightarrow D_s^+ \gamma$  decay, without explicit reconstruction of the  $D_s^+$ . To extract the num-

ber of partially reconstructed events, we compute the "missing mass"  $m_{miss}$  recoiling against the  $D^{*-}\gamma$  system assuming that a  $B^0 \rightarrow D^{*-}D_s^{*+} \rightarrow (\bar{D}^0\pi^-)(D_s^+\gamma)$  decay took place. For signal events,  $m_{miss}$  peaks at the  $D_s$  mass. We find, with this method, the following branching ratio :  $\mathcal{B}_1 \equiv \mathcal{B}(B^0 \rightarrow D^{*-}D_s^{*+}) = (1.88 \pm 0.09 \pm 0.17) \%$  which is in agreement with the factorization model prediction :  $\mathcal{B}(B^0 \rightarrow D^{*-}D_s^{*+})_{theo} = (2.4 \pm 0.7) \%$ . The second method uses a full reconstruction technique of the decay chain  $B^0 \rightarrow D^{*-}D_s^{*+}$  where the  $D_s$  candidate is reconstructed in the mode :  $D_s^+ \rightarrow \phi\pi^+ \rightarrow (K^+K^-)\pi^+$ . We measure the branching ratio  $\mathcal{B}_2 \equiv \mathcal{B}(B^0 \rightarrow D^{*-}D_s^{*+}) \times \mathcal{B}(D_s^+ \rightarrow \phi\pi^+) = (8.81 \pm 0.86_{stat}) \times 10^{-4}$ .

From the ratio  $\mathcal{B}_2/\mathcal{B}_1$ , where many systematics cancel out, we get a precise measurement of :  $\mathcal{B}(D_s^+ \rightarrow \phi\pi^+) = (4.81 \pm 0.52 \pm 0.38) \%$ . [9]. which shows a different central value and an improvement on the uncertainty by about a factor of two compared to previous measurements [2].

## 2.2. Search for the rare decays $\bar{B}^0 \rightarrow D^{(*)0}\gamma$

Within the standard model, the rare decay  $\bar{B}^0 \rightarrow D^{(*)0}\gamma$  is dominated by the W-boson exchange process. Its branching fraction is estimated to be of the order of  $10^{-6}$  but the presence of a large  $q\bar{q}$  g (color octet) component in the wave function of the  $B$  meson may reduce the color suppression enough to enhance the branching fraction by a factor of 10. A limit of  $\mathcal{B}(\bar{B}^0 \rightarrow D^{(*)0}\gamma) < 5.0 \times 10^{-5}$  at 90% CL has been published by the CLEO collaboration. With 87.8 million of  $B\bar{B}$  pairs, we set an upper limit of  $\mathcal{B}(\bar{B}^0 \rightarrow D^{(*)0}\gamma) < 2.5 \times 10^{-5}$  at 90% CL [10] in agreement with the theoretical expectations.

## 2.3. Search for the rare decays $B^+ \rightarrow D^{(*)+}K^0$

This decay is expected to occur via a pure annihilation diagram. Such processes provide interesting insights into the internal dynamics of  $B$  mesons. This kind of diagram cannot be calculated in QCD factorization since both quarks play a role. The amplitudes are expected to be suppressed, with respect to the amplitudes of spectator quark trees, by a factor  $f_B/m_B \approx 0.04$ .

The branching fractions are expected to be of the order of  $10^{-8}$  and have never been observed. Some studies [11] indicate, though, that processes with a spectator quark can contribute to annihilation-mediated decays by *rescattering* and the branching ratio is expected to raise up to  $10^{-5}$  if large rescattering occurs [11]. We reconstruct the two decay modes  $B^+ \rightarrow D^{*+}K_s^0$  and  $B^+ \rightarrow D^+K_s^0$  within a sample of 226 million of  $B\bar{B}$  pairs. We do not see any significant excess of signal, we therefore set the upper limits at 90 % CL :  $\mathcal{B}(B^+ \rightarrow D^+K_s^0) < 0.5 \times 10^{-5}$  and  $\mathcal{B}(B^+ \rightarrow D^{*+}K_s^0) < 0.9 \times 10^{-5}$  thus beginning to constrain the rescattering effects.

## 2.4. Search for the rare decays $B^- \rightarrow D_s^{(*)-}\phi$

In this other annihilation process  $B^- \rightarrow D_s^{(*)-}\phi$ , the branching fraction is expected to be suppressed in the standard model down to  $10^{-6}$ - $10^{-7}$ . Searches of  $B^- \rightarrow D_s^{(*)-}\phi$  decays could be sensitive to the new physics (NP) contributions such as Higgs doublet model which predicts a branching fraction of the order of  $10^{-5}$  or the minimal supersymmetric model with R-parity violation which predicts  $10^{-4}$ . Upper limits from CLEO are respectively 3.2 and  $4.0 \times 10^{-4}$  at 90% CL. Based on 234 million of  $B\bar{B}$  pairs, and reconstructing  $D_s^-$  into  $\phi\pi^-$  we have found no evidence for  $B^- \rightarrow D_s^{(*)-}\phi$  decays. We set upper limits at 90% CL for:  $\mathcal{B}(B^- \rightarrow D_s^-\phi) < 1.8 \times 10^{-6}$  and for  $\mathcal{B}(B^- \rightarrow D_s^{*-}\phi) < 1.1 \times 10^{-5}$  [12] using the new BABAR  $\mathcal{B}(D_s^- \rightarrow \phi\pi^-)$  value [section 2.1]. Our limits are more than two orders of magnitude lower than those of CLEO ruling out the two mentioned NP models.

## 2.5. Search for $B \rightarrow J/\psi D$ Decays

The spectra of the momentum of inclusive  $J/\psi$  mesons in the  $\Upsilon(4S)$  rest frame observed by CLEO and by BABAR, compared with calculations using non-relativistic QCD (NRQCD), show an excess at low momentum, corresponding to a branching fraction of approximately  $6 \times 10^{-4}$ . Many hypotheses have been proposed to explain this result but no experimental evidence has been found to support them. The presence of  $b\bar{u}c\bar{c}$  components (intrinsic charm) in

the  $B$ -meson wave function has also been suggested to enhance the branching ratio of decays such as  $B \rightarrow J/\psi \bar{D}(\pi)$  to the order of  $10^{-4}$  while perturbative QCD predicts a branching ratio for  $B \rightarrow J/\psi \bar{D}$  of  $10^{-8}$ - $10^{-9}$ . We test the decay channels  $B \rightarrow J/\psi D$  within a sample of 124 million of  $B\bar{B}$  pairs. We do not find any evidence of signal and obtain upper limits of  $1.3 \times 10^{-5}$  for  $B^0 \rightarrow J/\psi \bar{D}^0$  and  $1.2 \times 10^{-4}$  for  $B^+ \rightarrow J/\psi D^+$  at 90 % CL. Therefore, intrinsic charm is ruled out as the explanation of low momentum  $J/\psi$  excess in  $B$  decays. More details on this analysis can be found in reference [13].

## 2.6. Production and decay of the $\Xi_c^0$ and $\Omega_c^0$ at BABAR

We present a study of the  $\Xi_c^0$  ( $csd$ ) [14], and  $\Omega_c^0$  ( $ssc$ ) [15] charmed baryons using for the former a luminosity of  $116.1 \text{ fb}^{-1}$  through two decay modes :  $\Xi_c^0 \rightarrow \Omega^- K^+$  and  $\Xi_c^0 \rightarrow \Xi^- \pi^+$ . We measure, the ratio of the two decay rates to be  $0.294 \pm 0.018 \pm 0.016$  which is compatible with the prediction, in a spectator quark model calculation, of 0.32. For  $\Omega_c^0$ , we use  $230 \text{ fb}^{-1}$  and we reconstruct the baryon through three decay modes to compare the branching fractions [B1] :  $\Omega_c^0 \rightarrow \Omega^- \pi^+$ , [B2] :  $\Omega_c^0 \rightarrow \Omega^- \pi^+ \pi^- \pi^+$  and [B3] :  $\Omega_c^0 \rightarrow \Xi^- K^- \pi^+ \pi^+$ . We find the branching fraction ratios  $[B3]/[B1] = 0.31 \pm 0.015 \pm 0.040$  and  $[B2]/[B1] < 0.30$  at 90% CL. We also measure the  $p^*$  distribution of both charmed baryons, in the  $\Upsilon(4S)$  frame, in order to study the production mechanisms in both  $c\bar{c}$  and  $B\bar{B}$  events. We find a double-peak structure in the  $p^*$  spectrum of either baryon. This is due to two production mechanisms: the peak at lower  $p^*$  is due to charmed baryon production in  $B$  meson decays (first observation in the case of  $\Omega_c^0$ ) and the peak at higher  $p^*$  is due to charmed baryon production from the  $c\bar{c}$  continuum. From these spectra we compute the cross-section of the production of  $\Xi_c^0$  in continuum :  $\sigma(e^+e^- \rightarrow c\bar{c} \rightarrow \Xi_c^0 X) \times \mathcal{B}(\Xi_c^0 \rightarrow \Xi^- \pi^+) = (388 \pm 39 \pm 41) \text{ fb}$  and the rate of  $\Xi_c^0$  production in  $B$  decay :  $\mathcal{B}(B \rightarrow \Xi_c^0 X) \times \mathcal{B}(\Xi_c^0 \rightarrow \Xi^- \pi^+) = (2.11 \pm 0.19 \pm 0.25) \times 10^{-4}$ .

The high rate of  $\Xi_c^0$  production at low  $p^*$  in  $B$  decays (below 1.2 GeV/c) implies that the in-

variant mass of the recoiling antibaryon system is typically above 2.0 GeV/c<sup>2</sup>. This can be explained naturally by a substantial rate of charmed baryon pair production through the  $b \rightarrow c\bar{c}s$  weak decay process which was observed indirectly in a previous BABAR analysis [16].

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